An efficient cost-sharing program to reduce nonpoint-source contamination: theory and an application to groundwater contamination

C.S. Kim · G.D. Schaible · S.G. Daberkow

Abstract This research evaluates the economics of cost-sharing improved irrigation technologies to reduce agricultural, nonpoint-source contamination. Irrigation and fertilization inefficiencies are modeled within a nonjoint production process to evaluate both private and public costs of technology adoption and its effect on groundwater nitrate-contamination levels. A central Nebraska application indicates that even without a current government subsidy, a farmer is economically better off switching from gravity-flow to surge-flow irrigation rather than a center-pivot system. An annual government subsidy of $22.50 (US$) per hectare per year is required over the life of a center-pivot system to make the farmer financially indifferent. However, cost-sharing center-pivot adoption improves the groundwater contamination level, while other irrigation systems result in continued deterioration of groundwater quality.

Key words Cost-share · Irrigation · Nitrogen fertilizer · Nonjoint production

Introduction

A number of public policies and programs, such as regulations, taxes, crop land retirement, or technical assistance are available to address agricultural resource contamination problems (US Department of Agriculture 1997).

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However, cost-sharing programs have been a traditional policy tool used to encourage producers to adopt resource conserving and/or environmentally beneficial agricultural practices. In response to increased public concern about nonpoint-source contamination, the U.S. Congress established as part of the 1996 Farm Act, the agricultural cost-share program known as the Environmental Quality Incentive Program (EQIP). Since nitrogen fertilizer is highly water-soluble, cost-share programs are primarily designed to encourage farmers to adopt water-conserving, contamination-reducing irrigation technologies. Cost-share programs typically are voluntary, with taxpayers (in the case of EQIP) subsidizing up to 75% of the selected project cost of the conservation or contamination-reducing practice or investment (in the case of structures or equipment). Financial assistance to farmers under EQIP is designed to ensure the maximum level of environmental benefits possible per public dollar expended. Recent research, however, has been somewhat critical of agricultural cost-share programs. Davies (1997) concluded that the voluntary nature of these incentive payment programs has not achieved much beyond good intentions. Ervin (1997) argues that such policies have not secured protection against excessive soil erosion or water contamination despite considerable outlays.
Economists who have examined agricultural, nonpoint-source contamination problems have viewed the production process as a problem of joint production where both outputs, crops and nonpoint-source contamination, are produced using the same nitrogen fertilizer inputs employed by farmers (Anderson and others 1985; Larson and others 1996). However, Kim and others (1997, 1999) have demonstrated that in the case of nitrogen fertilizer use and groundwater irrigated agriculture, the production process is one of nonjoint production rather than joint production. Mis-specifying the production process results in overestimated economic benefits, and both supra-optimum nitrogen fertilizer use and an increased stock of nitrates in groundwater.
A second issue associated with evaluating an agricultural cost-share program concerns the relative size of the cost share between the government (taxpayers) and the individual farm operator. The adoption of a new agricultural technology or practice which reduces runoff or leaching

of an agri-chemical results in greater profits for the farmer, since less of the input is applied and increased resource efficiency can enhance productivity. Society also benefits from the adoption of a resource-conserving technology through the following: (1) a reduction in the opportunity costs associated with producer input-use inefficiency; (2) fewer resources devoted to cleaning the contaminated resource such as nitrate removal from drinking water; (3) improved human health or less demand for health service; and/or (4) lowered risk of ecological damage such as improved habitat for endangered species. Of course, all of these benefits must be weighed against the cost of adopting the new technology or practice. Presumably, if private benefits are sufficiently large relative to adoption costs, farmers will adopt the technology without a cost-share program. If private benefits are insufficient to encourage voluntary adoption, then the public sector may be justified in sharing the cost of adoption, particularly if the public plus private benefits exceed adoption costs. Quantifying the relative shares of public and private benefits from technology adoption then, are also critical economic concerns for any cost-share policy which aims to reduce agricultural-based nonpoint-source contamination.

This paper sets out to examine rigorously the economics of a cost-share program as it may be applied to encourage adoption of technologies and/or practices intended to reduce the risks of groundwater and surface-water contamination associated with nitrogen fertilizer use in irrigated agriculture. Research results demonstrate that, under certain economic circumstances, both agricultural producers and society benefit from such programs.

This paper begins by formally recognizing the nonjoint nature of irrigated agricultural production and agricultural resource contamination within the context of an economic framework. Then, a theoretical model is developed which captures both economic and environmental characteristics of the producer production decision process. The model allows one to derive the optimal government cost-share needed to encourage farmers to adopt improved irrigation technologies or practices intended to reduce nonpoint-source groundwater contamination. Finally, the model is used to quantify both the private and public benefits of adopting a specific technology designed to increase the use-efficiency of contamination-causing agricultural inputs. Factor-demand relationships for irrigation water and nitrogen fertilizer that correctly recognize input-use losses are used to identify farmer costs associated with input-use inefficiency, related social costs, and the economic benefits derived from reducing input-use inefficiency.

The model is then applied to farm-level data from Central Nebraska to evaluate the private and social economic benefits of government-subsidized irrigation technology investments and their effects on the groundwater contamination level. Because the adoption of an improved irrigation technology affects both the rate of leaching and the amounts of irrigation water and nitrogen fertilizer use, economic benefits of improved irrigation technology are evaluated for both irrigation water and nitrogen fertilizer use.

Nonjoint irrigated production technology

A number of studies have examined the agricultural nonpoint-source contamination problem, recommending the use of taxing policies to encourage reduced use of contamination-causing agri-chemicals (Choi and Feinerman 1996; Fleming and others 1995; Hrubocak and others 1990; Kim and others 1993; Larson and others 1996; Shortle and Dunn 1986). However, these studies viewed the production process as a problem of joint production, where both crops and nonpoint-source contamination are produced using the same input quantity. This perspective can be mathematically expressed as: $Y=f(n)$ and $Z=h(n)$, where Y is crop output, n is nitrogen fertilizer applied, and Z is nonpoint-source contamination.

Unlike the case of burning coal that generates energy and smoke, the assumption of joint production associated with nitrogen fertilizer use is somewhat misleading. Traditional crop production functions assume that all variable inputs, including irrigation water and nitrogen fertilizers, are fully employed to produce crop output. However, a portion of applied nitrogen fertilizer is lost through leaching, runoff, denitrification or volatilization. Only a portion of applied nitrogen fertilizer is used for crop growth in the crop production process. Therefore, the crop production process and the generation of nonpoint-source contamination is more appropriately characterized as a nonjoint production process, and for nitrogen fertilizer, can be represented as: $Y=f(\sigma n)$, $Z=h[(1-\sigma)n]$, and $\Pr[\sigma n \cap (1-\sigma)n]=\phi$, where σ is the fertilization efficiency coefficient, Pr is the probability operator, and ϕ is the empty or null set.

Estimation of a crop response function to nitrogen fertilizer assumes that crop production and groundwater contamination from nitrates are characterized as nonjointness in input quantities (Kohli 1983). If the crop production and groundwater contamination are characterized as jointness in output, a crop production function can not be estimated (Shumway and others 1983). Figure 1 demonstrates the conceptual difference between joint and nonjoint production perspectives. The production of crop and nonpoint contamination in agriculture is nonjoint because given an input application technology, the total nitrogen fertilizer use is allocated between two separate production processes, one for crop-growth/output and one which results in nonpoint contamination. Recognizing the unique character of agricultural production is particularly important when evaluating the economic effects of public sector conservation or environmentally-conscience programs. The following model structure accounts for this unique production process by differentiating, for both irrigation water and nitrogen fertilizer, ap-

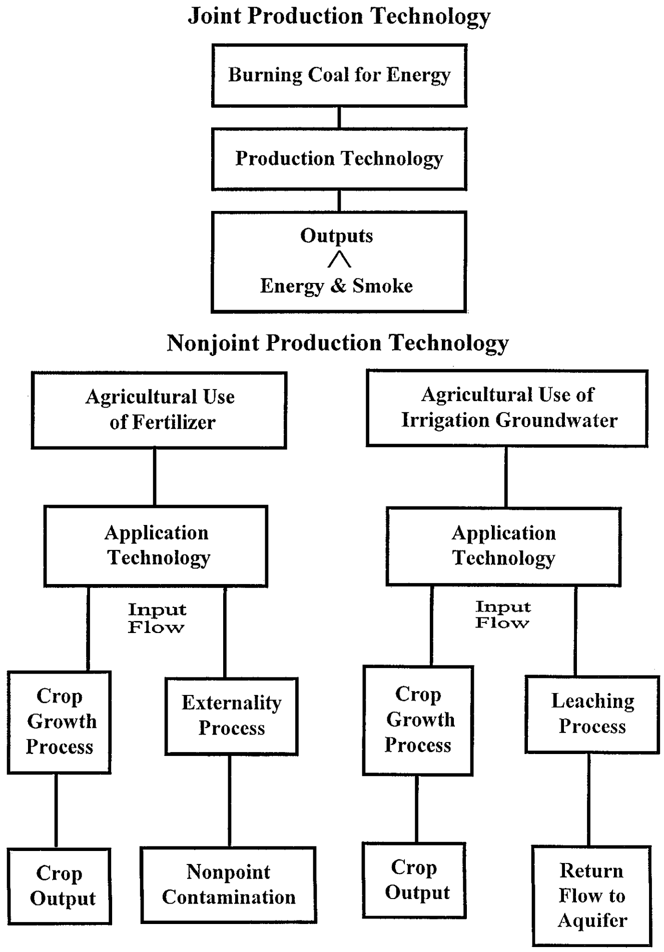

Fig. 1
Joint and nonjoint production technologies

plied input use between crop-growth consumptive use and nonpoint contamination.

Economic benefits from adoption of an improved irrigation technology

The model development begins with the estimation of a crop response function to irrigation water and nitrogen fertilizer. Even though some evidence indicates that plant-level crop response functions may be more correctly estimated by the von Liebig model (Ackello-Ogutu and others 1985), aggregate production functions for estimating crop response across fields or regions with heterogeneity or nonuniformities in the distribution of inputs, such as irrigation water and nitrogen fertilizer, will result in smooth nonlinear functions that are concave with positive marginal products (Berck and Helfand 1990). Consequently, the normalized-quadratic profit function has been frequently used to characterize the economic benefits (returns) of agricultural production technology (Huffman and Evenson 1989; Shumway 1983). This functional specification imposes homogeneity in prices and is self-dual. Furthermore, the normalized-quadratic profit function is as good as any other flexible functional form of a profit function with respect to Allen-Uzawa partial-substitution elasticities or price and fixed-factor elasticities (Thomson and Langworthy 1989). More importantly, the factor demand functions derived from the normalized-quadratic profit function are linear. The use of linear irrigation water and nitrogen fertilizer demand functions, as in the case of this paper, are easily tractable mathematically.

Irrigation water

There are both farmer and social costs associated with farm-level irrigation inefficiency (Kim and Schaible 1997). To evaluate these costs and to estimate the economic benefits of improved irrigation efficiency at the farm-level, the following discussion first identifies the difference between consumptive and applied irrigation water demand functions. Second, the discussion then correctly specifies economic benefits to a farmer for irrigation water use, and finally, a measure identifies the social costs and total economic benefits associated with a farmer shifting from an existing to an improved irrigation technology.

To begin with, let the crop-water production relationship for a farmer based on irrigation water applied be quadratic as follows:

$$Y(W_i) = aW_i - (b/2)W_i^2,\ a,b>0,\ \delta Y/\delta W_i>0 \text{ and } \delta^2 Y/\delta W_i^2<0 \quad (1)$$

for $i=1, 2,...m$, where Y is output and W_i is the amount of irrigation water applied with the ith irrigation technology. The irrigation water demand function associated with the ith irrigation system is obtained from Eq. 1 as follows:

$$P_w = P_Y[\delta Y(W_i)/\delta W_i] = P_Y[a - bW_i] \quad (2)$$

where P_w is the marginal benefit of W_i, and P_Y is output price.

While the crop production function in Eq. 1 assumes that all irrigation water applied, W_i, is fully employed in the production process, only a portion of the irrigation water applied is actually used (consumed) for crop growth. To derive a consumptive water demand function, consistent with a nonjoint production perspective, let W_c be the crop's consumptive-use quantity of irrigation water, such that:

$$W_c = \gamma_i W_i \text{ for } i=1, 2, \dots m, \quad (3)$$

where γ_i $(0<\gamma_i<1)$ is a coefficient of irrigation efficiency associated with the ith irrigation system. Since the actual crop-water production relationship must be correctly specified in terms of consumptive irrigation water use, Eq. 3 is inserted into Eq. 1 and is represented as follows:

$$Y(W_c) = (a/\gamma_i)W_c - (b/2\gamma_i^2)W_c^2 \text{ for } i=1, 2, \dots m,\ \delta Y/\delta W_c>0 \text{ and } \delta^2 Y/\delta W_c^2<0. \quad (4)$$

The irrigation water demand function obtained from Eq. 4 is then represented by:

$$P_w = P_Y[\delta Y(W_c)/\delta W_c][\delta W_c/\delta W_i] \quad (5)$$
$$= P_Y[a-(b/\gamma_i)W_c], \text{ for } i=1,2,\ldots,m.$$

To generalize the relationship between the consumptive and applied irrigation water demand functions, first let the consumptive irrigation water demand function (5) be rewritten as follows:

$$P_w = a_o - b_c W_c, \text{ where } a_o = aP_Y \text{ and } b_c = (b/\gamma_i)P_Y. \quad (6)$$

Second, using information from Eqs. 3 and 6, the applied irrigation water demand function in Eq. 2 can be represented in generalized form as follows:

$$P_w = a_0 - (\gamma_i b_c)W_i, \quad (7)$$
$$= a_0 - b_i W_i \text{ where } b_i = bP_Y = \gamma_i b_c \text{ for } i=1,2,\ldots,m.$$

These farm-level water demand functions can be represented graphically. The curve AD_c in Fig. 2 represents the farmer's consumptive irrigation water demand function for the ith irrigation system presented in Eq. 5, or equivalently Eq. 6. The curve AD_i represents the irrigation water demand function based on the amount of irrigation water applied with the ith irrigation system as represented in Eq. 2, or equivalently Eq. 7.

Economic benefits resulting from irrigation water use are measured with Eq. 6, represented by the area underneath the curve AD_c, regardless of the type of irrigation technology, as follows:

$$B(W_c:P_w) = \int_0^{W_c} [a_0 - b_c x]\,\delta x \quad (8)$$
$$= [a_0 W_c - (b_c/2)(W_c)^2], \text{ or equivalently,}$$
$$= \gamma_i[a_0 W_i - (\gamma_i b_c/2)W_i^2] \text{ from Eq. 3,}$$
$$= \gamma_i[a_0 W_i - (b_i/2)W_i^2] \ (i=1,2,\ldots,m),$$

where x is the variable of integration and $b_c = b_i/\gamma_i$ from Eq. 7. Economic benefits presented in Eq. 8 represents the area $0AD_c$ in Fig. 2. Economic benefits, $B(W_i:P_w)$, estimated from the applied irrigation water demand function in Eq. 2, or equivalently Eq. 7, are represented as follows:

$$B(W_i:P_w) = \int_0^{W_i} [a_0 - b_i x]\,\delta x \quad (9)$$
$$= [a_0 W_i - (b_i/2)W_i^2] \text{ for } i=1,2,\ldots,m,$$

which represents the area $0AD_i$ in Fig. 2.

By comparing Eqs. 8 and 9, one can derive the following condition (Kim and others 1997; Kim and Schaible 1997): $B(W_c:P_w) = \gamma_i B(W_i:P_w)$ for $i=1,2,\ldots m$. This result indicates that economic benefits estimated using an irrigation water demand function based on applied water as presented in Eq. 7, and measured by the area $0AD_i$ in Fig. 2, would be overestimated by a portion attributable to the irrigation water lost through runoff, evaporation and leaching, or the rate of irrigation inefficiency, $(1-\gamma_i)$. This result also implies that there are losses in economic benefits, equivalent to $(1-\gamma_i)B(W_i;P_w)$, as a result of the irrigation inefficiency associated with the ith irrigation system.

For a given per unit cost of irrigation water C_w ($ per hectare-meter), total economic benefits resulting from irrigation water use (for an irrigation system) are represented by the area $0AEW_c$ and associated irrigation water costs are represented by the area $0C_wFW_i$, so that net economic benefits resulting from this irrigation water use are represented by the area C_wAE less the area W_cEFW_i. Total costs resulting from the irrigation inefficiency associated with the ith irrigation system are represented by the area W_cEAFW_i, which is the sum of social opportunity costs (the area EAF) and additional farmer costs (the area W_cEFW_i). The area W_cEFW_i, which represents the farmer's increased water costs due to the inefficiency associated with the ith irrigation technology, $ICF_w(i)$, is measured from Fig. 2 as follows:

$$ICF_w(i) = C_w(W_i - W_c) = C_w(1-\gamma_i)W_i \text{ from Eq. 3,} \quad (10)$$
$$= C_w(a_0 - C_w)[(1-\gamma_i)/b_i] \text{ from Eq. 7 for } i=1,2,\ldots,m.$$

Since theory tells us that economic surplus generated from activity in an input market measures scarcity rents to producers plus consumer's surplus in the product market under general-equilibrium competitive conditions (Just and Hueth 1979), the area EAF represents social benefits foregone or net social economic costs, $NSC_w(i)$, resulting from the irrigation inefficiency associated with the ith irrigation technology. This cost is measured from Fig. 2 as follows:

$$NSC_w(i) = 0.5(A - C_w)(W_i - W_c) \quad (11)$$
$$= 0.5(a_0 - C_w)(1-\gamma_i)W_i \text{ where } A = a_0,$$
$$= 0.5(a_0 - C_w)^2[(1-\gamma_i)/b_i] \text{ from Eq. 7 for}$$
$$i=1,2,\ldots,m.$$

Consequently, total economic costs resulting from the irrigation inefficiency associated with the ith irrigation technology, $TC_w(i)$, are defined as the sum of the additional water costs to farmers presented in Eq. 10 and the net social economic costs presented in Eq. 11, and are represented as follows:

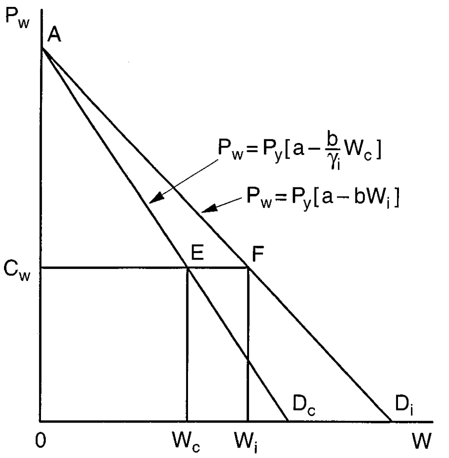

Fig. 2
The consumptive-use irrigation water demand curve (D_c), and the irrigation water demand curve (D_i) based on an application rate

$$TC_w(i) = ICF_w(i) + NSC_w(i) = 0.5[a_0^2 - C_w^2][(1-\gamma_i)/b_i] \text{ for } i = 1, 2, \ldots, m. \quad (12)$$

Now assume that there are two irrigation technologies, i and j, where the jth irrigation system is associated with an improved irrigation technology. Economic benefits to farmers, $EBF_w(ij)$, resulting from reducing irrigation water costs as a result of switching to the jth irrigation system from the ith system are represented by:

$$EBF_w(ij) = ICF_w(i) - ICF_w(j) = C_w(a_0 - C_w)[(1-\gamma_i)/b_i - (1-\gamma_j)b_j]. \quad (13)$$

The reduction in net social economic costs, or equivalently the net social economic benefits, $NSB_w(ij)$, as a result of switching to the jth irrigation system from the ith irrigation system, are estimated by:

$$NSB_w(ij) = NSC_w(i) - NSC_w(j) = 0.5(a_0 - C_w)^2[(1-\gamma_i)/b_i - (1-\gamma_j)b_j]. \quad (14)$$

Finally, total economic benefits, $TEB_w(ij)$, resulting from switching to the jth irrigation system from the ith system are represented by:

$$TEB_w(ij) = EBF_w(ij) + NSB_w(ij) = 0.5(a_0^2 - C_w^2)[(1-\gamma_i)/b_i - (1-\gamma_j)b_j]. \quad (15)$$

Nitrogen fertilizer

Since nitrogen fertilizer is highly water soluble, the amount of nitrogen fertilizer lost through leaching and runoff depends largely on the adopted irrigation technology in irrigated crop production, as well as other factors such as soil type and topography, which affect the amounts of both irrigation water and nitrogen fertilizer applied in crop production. For those areas where groundwater is the primary water source for irrigation, nitrates in groundwater are another source of nitrogen for crops. Therefore, the nutrient cycle must be considered in farm-level economic analysis associated with the nonpoint-source groundwater contamination problem (Kim and others 1996).

Let n_i and n_c be the amount of nitrogen fertilizer applied with the ith irrigation system and the consumptive use of nitrogen fertilizer, respectively, such that:

$$n_c = \sigma_i n_i \text{ for } i = 1, 2, \ldots, m, \quad (16)$$

where σ_i ($0 < \sigma_i < 1$) is a coefficient of fertilization efficiency associated with the ith irrigation technology. Furthermore, let the estimated crop nitrogen-fertilizer production function be quadratic in the amount of nitrogen fertilizer use, and represented as follows:

$$Y(n_i + \kappa_i N) = \alpha(n_i + \kappa_i N) - (\beta/2)(n_i + \kappa_i N)^2, \quad (17)$$

where α and β are nonzero positive constants, κ_i is a fractional coefficient which measures the ratio of the irrigation water applied per hectare (using the ith irrigation technology) to the amount of groundwater available per hectare from the underlying aquifer, and N is the stock of nitrates in groundwater. The nitrogen fertilizer demand function associated with the ith irrigation system, based on nitrogen applied and accounting for the nutrient cycle, is derived from Eq. 17 and is represented as follows:

$$P_n = P_Y[\delta Y(n_i + \kappa_i N)/\delta n_i] = P_Y[(\alpha - \beta\kappa_i N) - \beta n_i] \text{ for } i = 1, 2, \ldots, m, \quad (18)$$

where P_n represents the marginal benefits resulting from nitrogen fertilizer use.

Similar to irrigation water use, not all applied nitrogen fertilizer is consumptively used by the crop-growth process. Therefore, when the crop production function in Eq. 17 is correctly specified based on consumptive nitrogen fertilizer use, the production for the ith irrigation system is represented as follows:

$$Y(n_c + \sigma_i\kappa_i N) = \alpha[(n_c + \sigma_i\kappa_i N)/\sigma_i] - (\beta/2)[(n_c + \sigma_i\kappa_i N/\sigma_i]^2 \text{ for } i = 1, 2, \ldots, m. \quad (19)$$

The consumptive nitrogen-fertilizer demand function associated with the nutrient cycle then, is obtained from Eq. 19 and represented by:

$$P_n = P_Y[\delta Y(n_c + \sigma_i\kappa_i N)/\delta n_c][\delta n_c/\delta n_i] = P_Y[\alpha - \beta\kappa_i N - (\beta/\sigma_i)n_c] \text{ for } i = 1, 2, \ldots, m. \quad (20)$$

Research demonstrates that, even when the nutrient cycle is accounted for, economic benefits estimated using a nitrogen-fertilizer demand function based on application would be overestimated by the portion of nitrates lost through runoff, denitrification and leaching (Kim and others 1997, 1999). That is, $B(n_c + \sigma_i\kappa_i N : P_n) = \sigma_i B(n_i + \kappa_i N : P_n)$. This relationship can be shown by first integrating the consumptive nitrogen-fertilizer demand function presented in Eq. 20, resulting in:

$$\begin{aligned} B(n_c + \sigma_i\kappa_i N : P_n) &= P_Y \int_0^{n_c} [(\alpha - \beta\kappa_i N) - (\beta/\sigma_i)x]\,\delta x \\ &= P_Y[(\alpha - \beta\kappa_i N)n_c - (\beta/2\sigma_i)n_c^2] \\ &= \sigma_i P_Y[(\alpha - \beta\kappa_i N)n_i - (\beta/2)n_i^2] \\ &\text{for } i = 1, 2, \ldots, m, \end{aligned} \quad (21)$$

where $n_c = \sigma_i n_i$ from Eq. 16 and x is the variable of integration. Second, the integration of the applied nitrogen-fertilizer demand function, as presented in Eq. 18, results in the following:

$$\begin{aligned} B(n_i + \kappa_i N : P_n) &= P_Y \int_0^{n_i} [(\alpha - \beta\kappa_i N) - \beta x]\,\delta x \\ &= P_Y[(\alpha - \beta\kappa_i N)n_i - (\beta/2)n_i^2] \text{ for } i = 1, 2, \ldots, m. \end{aligned} \quad (22)$$

Then, after comparing Eqs. 21 and 22, the results indicate that σ_i times $B(n_i + \kappa_i N : P_n)$ from Eq. 22 equals $B(n_c + \beta\sigma_i\kappa_i N : P_n)$ from Eq. 21.

To generalize the relationship between the consumptive and applied nitrogen-fertilizer demand functions, first let the consumptive nitrogen-fertilizer demand function presented in Eq. 20 be rewritten as follows:

$$P_n = \alpha_0 - \beta_c n_c, \text{ where } \alpha_o = P_Y(\alpha - \beta\kappa_i N) \text{ and } \beta_c = P_Y(\beta/\sigma_i). \quad (23)$$

Second, the applied nitrogen-fertilizer demand function from Eq. 18 is rewritten in similar terms to allow a more general comparison with the consumptive nitrogen-fertilizer demand function presented in Eq. 23 as follows:

$$P_n = \alpha_o - (\sigma_i \beta_c) n_i. \tag{24}$$

These more general, fertilizer factor-demand relationships can then be used to identify increased farmer costs associated with fertilization inefficiency, and the economic benefits for a farmer and society associated with increased fertilization efficiency. Increased fertilization costs to a farmer, $ICF_n(i)$, resulting from the fertilization inefficiency associated with the ith irrigation technology is estimated by:

$$ICF_n(i) = C_n[n_i - n_c] = C_n(1-\sigma_i)n_i = C_n(\alpha_o - C_n)[(1-\sigma_i)/\sigma_i\beta_c], \tag{25}$$

where C_n is a per unit cost of nitrogen fertilizer. Meanwhile, the net social economic cost, $NSC_n(i)$, resulting from the fertilization inefficiency associated with the ith irrigation technology is estimated by:

$$\begin{aligned} NSC_n(i) &= 0.5(\alpha_0 - C_n)(n_i - n_c) \\ &= 0.5(\alpha_0 - C_n)^2[(1-\sigma_i)/\sigma_i\beta_c]. \end{aligned} \tag{26}$$

Therefore, the total economic cost resulting from the fertilization inefficiency associated with the ith irrigation technology, $TC_n(i)$, is defined as follows:

$$TC_n(i) = ICF_n(i) + NSC_n(i) = 0.5(\alpha_0^2 - C_n^2)[(1-\sigma_i)/\sigma_i\beta_c]. \tag{27}$$

Now, to estimate economic benefits of improved technology embodying improved fertilization efficiency, again assume that there are two alternative irrigation technologies *i* and *j*, where the *j*th irrigation system is associated with an improved irrigation technology. Then, the economic benefits to a farmer, $EBF_n(ij)$, resulting from the reduction of nitrogen fertilizer use as a result of switching to the jth irrigation technology from the ith technology are represented as follows:

$$\begin{aligned} EBF_n(ij) &= ICF_n(i) - ICF_n(j) \\ &= C_n[(\alpha_0 - C_n)[(1-\sigma_i)/\sigma_i\beta_c - (1-\sigma_j)/\sigma_j\beta_c]. \end{aligned} \tag{28}$$

The net social economic benefits of improved fertilization efficiency, $NSB_n(ij)$, resulting from switching from the *i*th to the *j*th irrigation technology are represented by:

$$\begin{aligned} NSB_n(ij) &= NSC_n(i) - NSC_n(j) \\ &= 0.5(\alpha_0 - C_n)^2[(1-\sigma_i)/\sigma_i\beta_c - (1-\sigma_j)/\sigma_j\beta_c]. \end{aligned} \tag{29}$$

Total economic benefits of improved fertilization efficiency, $TEB_n(ij)$, resulting from switching from the ith to the jth irrigation system are represented by:

$$\begin{aligned} TEB_n(ij) &= EBF_n(ij) + NSB_n(ij) \\ &= 0.5(\alpha_0^2 - C_n^2)[(1-\sigma_i)/\sigma_i\beta_c - (1-\sigma_j)/\sigma_j\beta_c]. \end{aligned} \tag{30}$$

Finally, aggregate total economic benefits for the farmer and society of improved water and fertilization efficiency, $TEB_{w+n}(ij)$, resulting from the adoption of an improved irrigation technology are represented as follows:

$$\begin{aligned} TEB_{w+n}(ij) &= TEB_w(ij) + TEB_n(ij) \\ &= 0.5[(a_0^2 - C_w^2)[(1-\gamma_i)/b_i - (1-\gamma_j)b_j] \\ &\quad + (\alpha_0^2 - C_n^2)[(1-\sigma_i)/\sigma_i\beta_c - (1-\sigma_j)/\sigma_j\beta_c]]. \end{aligned} \tag{31}$$

Aggregate total economic benefits to farmers alone of improved water and fertilization efficiency, $TEBF_{w+n}$, are represented by:

$$\begin{aligned} TEBF_{w+n}(ij) &= [EBF_w(ij) + EBF_n(ij)] \\ &= C_w(a_0 - C_w)[(1-\gamma_i)/b_i - (1-\gamma_i)b_j] \\ &\quad + C_n(\alpha_0 - C_n)[(1-\sigma_i)/\sigma_i\beta_c - (1-\sigma_j)/\sigma_j\beta_c]. \end{aligned} \tag{32}$$

These results indicate that in cases where the sum of increased capital costs and reduced net operating and maintenance costs associated with the adoption of an improved irrigation technology, $K(ij)$, is less than the aggregate total economic benefit to a farmer as presented in Eq. 32, a regulatory policy would likely be effective by penalizing those farmers not adopting an improved irrigation technology. On the other hand, in cases where the sum of increased capital costs and reduced net operating and maintenance costs for an improved irrigation system are greater than $TEBF_{w+n}(ij)$ in Eq. 32, but less than total economic benefits to farmers and society presented in Eq. 31, a farmer would be willing to incur additional costs, but only up to an amount equivalent to $TEBF_{w+n}(ij)$ in Eq. 32. In this situation, the farmer remains financially indifferent toward adoption of the improved irrigation technology if additional costs associated with the adoption of an improved irrigation technology, $K(ij)$, greater than $TEBF_{w+n}(ij)$, are financed by the government. In those cases where additional costs to farmers, $K(ij)$, are greater than the aggregate total economic benefits to farmers and society, as presented in Eq. 31, the farmer would remain willing to pay only additional costs equivalent to $TEBF_{w+n}(ij)$ in Eq. 32, and still remain financially indifferent, while the government pays all remaining costs, even those costs greater than $TEBF_{w+n}(ij)$. The cost-share between the government and farmers that encourages the technology adoption resulting in improved irrigation water use and fertilization efficiency is then given by:

$$\text{Government cost share} = [K(ij) - TEBF_{w+n}(ij)]/K(ij), \quad \text{iff } TEBF_{w+n}(ij) < K(ij). \tag{33}$$

Irrigation technology selection and its effects on groundwater quality

For a given soil type and topography, the amount of nitrogen fertilizer lost through leaching depends largely on the adopted irrigation technology. Therefore, the fertilization efficiency coefficient also changes as a result of the adoption of an improved irrigation technology. Let the change in the stock of nitrates in groundwater, $\dot{N}$, be represented by the following system of first-order differential equations:

$$\dot{N}_i(t) = \tau_i[n_i(t) + \kappa_i N_i(t)] - \rho_i N_i(t) \text{ for } i = 1, 2, \ldots, m, \tag{34}$$

where the subscript *i* represents the *i*th irrigation technology, τ_i represents the rate of nitrate leaching asso-

ciated with the ith irrigation technology such that $\tau_i < (1-\sigma_i)$, and ρ represents the rate of nitrate discharge from the stock of nitrates in groundwater, which is the sum of natural nitrate discharge due to groundwater flows and the rate of artificial nitrate discharge through pumping groundwater for irrigation. It is assumed in the hydrologic Eq. 34 that the leaching of nitrates into the groundwater would occur instantly. This is not an unusual occurance in many irrigated areas. In watershed areas underlaid by a shallow aquifer, particularly when the area is defined by sandy loam soils, the stock of nitrates in groundwater are often immediately affected after fertilization. This assumption is relevent here because a shallow aquifer underlying a watershed area with sandy loam soils defines the study area in the following empirical analysis. Furthermore, within the context of a competitive dynamic model of nitrogen fertilizer use, the omission of the time lag would affect neither the rate of fertilizer application nor the stock of nitrates in groundwater.
Let the fertilization efficiency be represented by $\sigma_i = (1-\tau_i-r_i)$, where r_i is the rate of nitrate loss through runoff and denitrification. Substituting Eq. 18 for applied nitrogen fertilizer demand for the ith irrigation system, $n_i(t)$, into Eq. 34 results in the following change in nitrate stocks:

$$\dot{N}_i(t) = \tau_i[(\alpha P_Y - C_n)/\sigma_i\beta_c] - \rho_i N_i(t) \text{ for } i = 1, 2, \ldots, m. \quad (35)$$

Then the time path of nitrate accumulation in groundwater is determined by solving the first-order differential Eq. 35 as follows:

$$N_i(t) = \theta_i + (N_o - \theta_i)\exp(-\rho_i)t \text{ for } i = 1, 2, \ldots, m, \quad (36)$$

where $N_o = N(t=0)$ and $\theta_i = [\tau_i(\alpha P_Y - C_n)/\rho_i\sigma_i\beta_c]$. Finally, the nitrate concentration level at the end of each irrigation system's life expectancy can be estimated by inserting area-specific economic and geohydrologic data into Eq. 36. The change in aquifer nitrate concentration levels associated with improved irrigation technologies will demonstrate water quality impacts. The time path of nitrogen fertilizer application is then obtained by inserting $N_i(t)$ from Eq. 36 into Eq. 18 and deriving $n_i(t)$ as follows:

$$n_i(t) = [(\alpha/\beta) - C_n/(\beta P_Y) - \kappa_i\mu_i] + \kappa_i(N_o - \mu_i)\exp(-\rho_i)t \text{ for } i = 1, 2, \ldots, m. \quad (37)$$

Application to Merrick County, Nebraska

The study area is located in Merrick county, Nebraska, where the observed nitrate concentration level in groundwater on average was 18.7 parts per million (ppm), according to a survey conducted by the Central Platte Natural Resources District (CPNRD) during the 1988–1990 period. Economic and geohydrologic data for the study area are presented in Table 1. The hydrologic data are obtained from Bentall (1975a, b); Exner and Spalding (1976) and Signor and others (1996). Data on the irrigation efficiency coefficients are obtained from Williams and others (1997). Data on groundwater quality, groundwater pumping costs, the amounts of nitrogen fertilizer and irrigation water applied during the period between 1988 and 1990 are obtained from a survey conducted by the CPNRD during the same period. Data on prices for corn and soybeans are from various volumes of Agricultural Statistics, National Agricultural Statistics Service, USDA. Nitrogen fertilizer price data are from Vroomen and Taylor (1992).
The fertilization efficiency coefficient associated with the ith irrigation technology is assumed to be identical with its irrigation efficiency coefficient for two reasons. First, estimates of irrigation water and nitrogen fertilizer losses through runoff and leaching from the Erosion Productivity Impact Calculator (EPIC) simulation model were unreliable, and second, nitrates are highly soluble and deep percolation into the aquifer generally carry only soluble substances due to the fact that the soil acts as a filter for the percolating water (Porter 1975).
Examination of EPIC-based simulation studies confirms these conclusions. The EPIC simulation model was recently used to estimate rates of nitrate leaching as well as fertilization efficiency coefficients (Chowdhury and Lacewell 1996; Larson and others 1996; Magleby and others 1995; Wu and others 1994). These authors conducted EPIC simulation runs at different fertilizer application levels for each combination of crop, soil type, and irrigation system. Each EPIC simulation run generated crop yield, the amounts of irrigation runoff and percolations, as well as the amounts of nitrogen fertilizer lost through runoff and leaching. Estimates of the amounts of nitrogen fertilizer lost through runoff and leaching were then regressed with the amounts of irrigation water and nitrogen fertilizer applied, which were used to estimate the rates of nitrate leaching and runoff. EPIC estimates for the amounts of irrigation water and fertilizer lost through runoff and leaching are somewhat variable. For instance, EPIC simulation results revealed that more than 77% of irrigation water applied with a conventional furrow irrigation system would be lost through percolation on a mid-Nebraska 15 county area with crete silt loam soil (Magleby and others 1995). Furthermore, EPIC results also showed that a great portion of irrigation water applied would be lost through runoff when using a conventional furrow irrigation system on silt roam soil. Therefore, the reliability of the EPIC estimates for the fertilization efficiency rate associated with the unreasonable rates of irrigation efficiency would be questionable.
Since most acreage in the CPNRD are allocated to continuous corn production to meet local feed demand for livestock production, we employed a multiple inputs – single output normalized profit function (Huffman and Evenson 1989; Shumway 1983) to estimate the supply of corn, the demand for nitrogen fertilizers, and the demand for irrigation groundwater. Pooled data for the period 1960–1990 was grouped for Buffalo, Hall, and Merrick counties which are located within the Nebraska Mid-State area (Kim and others 1999). The normalized price elasti-

Table 1
Economic and hydrologic parameters pertaining to Merrick county, Nebraska

	Symbol description	Parameter value
a_0	Per hectare inverse water demand intercept	1.37818
b_c	The slope of consumptive water demand	1.55783
b_1	The slope of water demand with a furrow irrigation system	1.01259
b_2	The slope of water demand with a tail-water recovery irrigation system	1.13722
b_3	The slope of water demand with a surge-flow irrigation system	1.16837
b_4	The slope of water demand with a center-pivot irrigation system	1.32416
α_o	Per hectare inverse nitrogen fertilizer demand intercept	1.4980
β_c	The slope of consumptive N-fertilizer demand	0.00984
β_1	The slope of N-fertilizer demand with a furrow irrigation system	0.00640
β_2	The slope of N-fertilizer demand with a tail-water recovery system	0.00718
β_3	The slope of N-fertilizer demand with a surge-flow irrigation system	0.00738
β_4	The slope of N-fertilizer demand with a center-pivot irrigation system	0.00836
ω	Saturated thickness (m)	45.72
m	Specific yield[a]	0.25
N_o	The stock of nitrates in the underlying aquifer at the base year (kg/ha)	715.5
P_Y	Unit price of corn ($/l)	0.0653
W_i	The observed (average) amount of irrigation water use (m/ha)[b]	0.991
C_w	Variable cost of pumping one hectare-meter of groundwater ($)	0.293
n_i	The observed amounts of nitrogen fertilizer use (kg/ha)	161.56
C_n	Unit cost of nitrogen fertilizer ($/kg)	0.38
γ_i	Irrigation efficiency coefficient and fertilization efficiency	
or σ_i	i=1 for a conventional furrow irrigation system	0.65
	i=2 for a tail-water recovery irrigation system	0.73
	i=3 for a surge-flow irrigation system	0.75
	i=4 for a center pivot irrigation system	0.85
τ_i	The rate of leaching	
	i=1 for a conventional furrow irrigation system	0.23
	i=2 for a tail-water recovery irrigation system	0.27
	i=3 for a surge flow irrigation system	0.15
	i=4 for a center pivot irrigation system	0.09
ρ_i	The rate of artificial discharge (ρ_i) or the ratio of the irrigation	
or κ_i	water applied per acre to the amount of groundwater available	
	per acre from the underlying aquifer (κ_i)	
	i=1 for a conventional furrow irrigation system	0.0375
	i=2 for a tail-water recovery irrigation system	0.0334
	i=3 for a surge flow irrigation system	0.0325
	i=4 for a center pivot irrigation system	0.0287

[a] Specific yield is defined as the unitless ratio of the volume of water a saturated rock or soil will yield under the influence of gravity to its own volume (Cleary and others 1992)

[b] Estimated based on 32% of total irrigated land for corn production in the CPNRD during 1989–1990 using sprinkler irrigation systems (primarily center pivots), and the remainder using primarily conventional furrow irrigation

cities of applied irrigation water and nitrogen fertilizer demands are estimated to be –0.27 and –0.34, respectively. Using these estimated price elasticities, parameters for both consumptive and applied per hectare irrigation water demand and per hectare nitrogen fertilizer demand functions are estimated using the procedure specified in Kim and others (1999), along with the efficiency, water use, and irrigation statisitcs presented in Table 1.

Social, as well as economic benefits to a farmer resulting from the adoption of an improved irrigation technology are estimated using the data for the study area presented in Table 1. Results are presented in Table 2. Results indicate that a farmer would be economically better off adopting a tail-water recovery irrigation system or a surge-flow irrigation system even without a government subsidy. These results are consistent with those reported by Williams and others (1997). The results also demonstrate that the aggregated total economic benefits for a farmer, $TEBF_{w+n}$, that are associated with the adoption of a center-pivot irrigation system are not large enough to offset its higher capital costs. These results most likely explain the reason why the adoption of a center-pivot irrigation system in the study area has been sluggish. The minimum government cost-share required to encourage the adoption of a center-pivot irrigation system is estimated to be $22.55 (US$) per hectare per year (Table 2).

Table 2
Economic benefits resulting from the adoption of improved irrigation technologies

	Irrigation System		
	Tail-water recovery	Surge-flow	Center-pivot
		($/hectare)[a]	
EBF_w	1.7665	2.1503	3.8113
NSB_w	3.2710	3.9823	7.0578
TEB_w	5.0375	6.1325	10.8690
EBF_n	7.1145	8.6743	15.4105
NSB_n	10.4625	12.7563	22.6625
TEB_n	17.5770	21.4305	38.0730
$TEBF_{w+n}$	8.8810	10.8245	19.2218
NSB_{w+n}	13.7335	16.7385	29.7203
TEB_{w+n}	22.6145	27.5630	48.9420
(A) Annuity of capital investment costs over furrow irrigation system (5% discount rate)[b]	4.83	4.83	59.98
(B) Annual labor and system maintenance costs over furrow irrigation system[c]	−11.90	−12.85	−18.20
(C) Rows (A)+(B)	− 7.07	− 8.03	41.78
(D) $TEBF_{w+n}$–(C)	15.95	18.85	−22.55

[a] All prices are represented by the 1990 price
[b] Capital investments for a conventional furrow, a tail-water recovery system, a surge-flow system and a center pivot irrigation system are assumed to be $587.5/ha, $637.5/ha, $637.5/ha and $1,210/ha, respectively (Williams and others 1997). A life expectancy of 15 years is assumed for each system
[c] Annual labor and system maintenance costs are assumed to be $1.10/ha–cm ($47.23/ha), $0.93/ha–cm ($35.33/ha), $0.93/ha–cm ($34.38/ha), and $0.88/ha–cm ($29.03/ha) for a conventional furrow, a tail-water recovery, surge-flow, and a low-pressure center pivot irrigation system, respectively (Williams and others 1997)

Table 3
Trajectories for the stock of nitrates in groundwater, $N_i(t)$

Irrigation technology	$N_i(t)=u_i+v_i\exp[-w_it]$			$N_i(t=15)$	
	u_i	v_i	w_i	(kg/hectar)	ppm
Conventional furrow irrigation system	1227.99	−512.49	0.0375	935.83	24.47
Tail-water recovery irrigation system	1441.14	−725.64	0.0334	1001.30	26.18
Surge-flow irrigation system	800.87	− 85.37	0.0325	748.27	19.56
Center-pivot irrigation system	480.13	235.37	0.0287	632.99	16.55

Extending this analysis using Eq. 36, the time path of nitrate accumulation in groundwater is estimated for each irrigation technology and presented in Table 3. Most major components of each irrigation system are assumed to have a 15-year life expectancy (Williams and others 1997), so that the amounts of nitrate accumulation in groundwater after the 15-year period are estimated by irrigation system as follows: $N_1(t=15)=935.83$ kg (24.47 ppm) for a conventional furrow irrigation system; $N_2(t=15)=1{,}001.30$ kg (26.18 ppm) for a tail-water recovery system; $N_3(t=15)=748.27$ kg (19.56 ppm) for a surge-flow irrigation system; and $N_4(t=15)=632.99$ kg (16.55 ppm) for a center-pivot irrigation system.
These results indicate that the groundwater contamination level would deteriorate (nitrates in terms of ppm increase) at a faster rate with a tail-water recovery system alone. This result is expected because while a tail-water recovery system has a higher irrigation efficiency than a conventional furrow system (0.73 vs. 0.65), it also has a higher rate of leaching than a conventional furrow system (0.27 vs. 0.23). Even the groundwater contamination level with a surge-flow irrigation system would continue to deteriorate, but at a decreasing rate. Only the center-pivot, sprinkler irrigation system reduces the groundwater contamination level from 18.7 ppm to 16.55 ppm after 15 years.
Currently, farmers in the CPNRD who adopt a surge-flow irrigation system can share the cost of such a system with the CPNRD. However, the CPNRD does not subsidize farmers for adopting a sprinkler irrigation system.

From a social-economic perspective, these results imply that it would be economically efficient and environmentally beneficial for the government (public sector) to cost-share the adoption of center-pivot irrigation systems rather than surge-flow irrigation systems. Furthermore, given the likelihood of even additional social benefits (not measured here) associated with safe drinking water supplies, as well as from potential ecological enhancement where hydrologic relationships may impact downstream flows, these results justify a government cost-share greater than the aggregate private (producer) economic benefits less the additional producer costs. In other words, results here likely justify an actual government cost share for this study area greater than $22.55 (US$) per hectare per year.

Conclusion

Most research in environmental economic policy analysis associated with nonpoint-source groundwater contamination from nitrogen fertilizer use have assumed that the production process of crop output and nonpoint-source contamination is a joint production process. As a consequence, economists have failed to recognize the losses in economic benefits associated with both irrigation and fertilization inefficiencies. Results from this study demonstrate that irrigation and fertilization inefficiencies generate economic costs to society and farmers, but that the economic losses due to these inefficiencies decline as a result of adopting improved irrigation technologies. Furthermore, results also demonstrate that there are environmental as well as economic reasons for a government cost-share program by characterizing the crop production process and the generation of nonpoint-source contamination as a nonjoint production process.

This paper evaluates the current EQIP cost-share program perspective associated with the voluntary adoption of an improved irrigation technology to reduce the risks of groundwater contamination from agricultural production acitivity. Since the adoption of an improved irrigation technology affects both the rate of leaching and the amounts of irrigation water and nitrogen fertilizer use, the economic benefits resulting from the adoption of an improved irrigation technology are evaluated for both irrigation water and nitrogen fertilizer use. The effects on the nitrate contamination level of adopting an improved irrigation technology are also evaluated under the assumption that the fertilization efficiency coefficient associated with each irrigation technology is identical with its irrigation efficiency coefficient. Considering the fact that nitrates are highly soluble and deep percolation into an aquifer generally will carry only soluble substances (Porter 1975), and that EPIC estimates for concurrent rates of both irrigation and fertilization inefficiencies are unreliable, the rate of irrigation efficiency may be considered a reasonable proxy for the rate of fertilization efficiency for the study area.

While farmers in the CPNRD who adopt a surge-flow irrigation system can share the cost of such a system with the CPNRD, the CPNRD does not subsidize farmers for adopting a sprinkler irrigation system. Results indicate that from a competitive economic efficiency perspective (without a government subsidy), a farmer would be economically better off adopting a surge-flow irrigation system. Economic benefits resulting from improving irrigation inefficiency are large enough to cover the capital costs associated with a surge-flow irrigation system, even though the groundwater contamination level with a surge-flow irrigation system continues to deteriorate, but at a decreasing rate. However, economic benefits resulting from the adoption of a center-pivot irrigation system are not large enough to offset its higher capital costs. Results indicate that a government subsidy of $22.55 (US$) per hectare per year is needed for farmers to adopt a center-pivot irrigation system and to remain financially indifferent, but the groundwater contamination level would improve from 18.7 ppm to 16.55 ppm after 15 years. The groundwater contamination level with a conventional furrow irrigation system would be 24.47 ppm after a 15-year life expectancy of the irrigation system. Consequently, these results imply that from a social perspective, it would be economically efficient and environmentally beneficial for the government to cost-share the adoption of center-pivot irrigation systems rather than surge-flow irrigation systems. In addition, human health and ecological benefits could possibly justify a government cost share greater than $22.55 (US$) per hectare per year.

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